Introduction

1. **Transducers**: Sensors and actuators are types of transducers, which transform signals or power from one energy form to another.
    - **Sensors** detect and monitor physical phenomena (like vibration, pressure, temperature) or chemical variations (like electrical conductivity or pH).
    - **Actuators** produce mechanical motion and force.
2. **Sensor Parts**:
    - **Sensing element**: Detects physical or chemical changes.
    - **Transducer**: Converts the detected signal to electrical form.
    - **Readout device**: Displays or interprets the signal.
3. **Sensor Performance**:
    - **Sensitivity**: Minimum detectable amount of a target substance.
    - **Resolution**: The smallest measurable change.
    - **Accuracy**: The closeness to the true value.
    - **Limit of Detection (LOD)**: The lowest quantity detectable.
    - **Response time**: Time it takes for the sensor to react to a signal.
    - **Recovery time**: Time it takes to return to baseline.
4. **MEMS (Microelectromechanical Systems)**:
    - MEMS technology involves tiny devices that can act as sensors or actuators, created using semiconductor materials.
    - MEMS devices are very small (microns in size) and are used for miniaturized electronic equipment, reducing cost and improving performance.
    - They operate on the principle of integrating mechanical components, sensors, actuators, and electronics on a silicon substrate.
5. **MEMS Sensors**:
    - **Applications**: MEMS are used in many fields such as gas sensing, humidity sensors, and detecting toxic gases.
    - **Materials Used**: Metal oxides like TiO2, SnO2, and ZnO are commonly used for gas detection.
    - **Challenges**: High sensitivity usually requires high temperatures, and there are selectivity issues in some sensors.
    - **Solution**: Combining metal oxides with noble metal nanoparticles (like Au, Pd, Pt) can improve performance.
6. **MEMS Fabrication**:
    - MEMS devices are made using microfabrication methods like deposition, patterning, and etching.
    - **MUMPs (Multi-User MEMS)**: A system for creating MEMS devices used in both academic and industrial research, including various fabrication techniques like PolyMUMPs, MetalMUMPs, and SOIMUMPs.
7. **MEMS Applications**:
    - MEMS devices are used in a wide range of fields, from industrial applications to consumer products, providing energy efficiency, small sizes, and low power consumption.
    - MEMS actuation and sensing technologies have made significant advances, supporting the growth of miniaturized electronic systems.
8. **Actuation and Sensing**:
    - **Actuation**: The efficiency of MEMS actuators depends on factors like power, control methods, compatibility, packaging, and cost-effectiveness.
    - **Sensing**: MEMS sensors are essential in applications like gas sensing, humidity detection, and toxic gas monitoring.

Overview of the Paper Structure:

- **Section II**: Introduction to MEMS.

- **Section III**: Review of actuation mechanisms (electrostatic, electrothermal, electromagnetic, and piezoelectric).
- **Section IV**: Overview of sensing mechanisms (piezoresistive, capacitive, and optical).
- **Section V**: Discussion of future prospects for MEMS-based devices.
- **Section VI**: Conclusion and future trends.

MEMS (Micro-Electro-Mechanical Systems):

- **Definition and History:**
  - MEMS technology began in 1954, first described by Smith in a paper on piezoresistors at Bell Telephone Labs.
  - MEMS is a broad term used for devices that combine microelectronics with micromachining, and it is known by various names like Microsystems Technology (MST) in Europe and Micromechanics in Asia.
- **Energy Domains:**
  - MEMS devices can detect and measure various energy forms, known as "energy domains." These include:
    1. **Electrical Domain**: Voltage, current, resistance, charge, etc.
    2. **Chemical Domain**: Composition, pH, concentration, reaction rates, etc.
    3. **Mechanical Domain**: Force, velocity, pressure, torque, etc.
    4. **Thermal Domain**: Temperature, heat, entropy, specific heat, etc.
    5. **Radiative Domain**: Intensity, wavelength, electromagnetic waves, UV radiation, etc.
    6. **Magnetic Domain**: Magnetic field strength, permeability, flux density, etc.
- **MEMS Device Categories:**
  - MEMS can be divided into different categories based on application and function:
    1. **Fluidic MEMS**: Used in flow and pressure sensors, valves, and pumps. Common in biological, chemical, and pharmaceutical applications.
    2. **RF MEMS**: Used for high-frequency signal transmission and changes (e.g., antennas, tunable capacitors).
    3. **Optical MEMS**: Devices designed to manipulate light (e.g., optical switches, filters).
    4. **Bio MEMS**: Devices designed to interact with biological systems, often used in drug delivery and medical analysis.
- **Applications and Benefits:**
  - MEMS devices are used across a range of applications, including consumer electronics, aerospace, biomedical instrumentation, military, and industrial uses.
  - Key benefits include:
    1. **Low cost** due to potential for mass production.
    2. **Low power consumption** and **high sensitivity** due to their small size.
    3. **Lightweight**, **high resolution**, and **stability**.
    4. **Ease of integration** with other devices and systems.
  - Examples of applications: Gyroscopes, pressure sensors, accelerometers, and sensors for chemical, motion, force, and biomedical measurements.
- **Working Principles of MEMS Devices:**
  - **Static Mode**: The device is affected by surface adsorption or changes in the chemical bonding, causing deformation or stress, which can be detected by sensors.
  - **Dynamic Mode**: The device operates based on a mechanical resonant frequency, where the maximum resonance is determined by the spring constant and the mass of the device. The change in resonance frequency helps detect and measure the desired parameter.
- **Key Parameters for MEMS Sensors:**
  - **Sensitivity**: Ability to detect small changes.
  - **Resolution**: The smallest measurable change.
  - **Quality Factor (Q)**: High Q is required for sensitive measurements and resolution.

Actuation Techniques for MEMS-Based Devices:

- **Actuation Mechanism:**
  - Actuation refers to the process that transforms input energy into motion of a microstructure in MEMS devices. Different actuation techniques are used to drive the motion, including:
    1. **Electrostatic Actuation**: Uses the force between electrically charged plates to create motion.
    2. **Electrothermal Actuation**: Utilizes heat generated by current passing through a material (microheaters) to create motion.
    3. **Electromagnetic Actuation**: Relies on magnetic fields to produce motion.
    4. **Piezoelectric Actuation**: Uses changes in material shape under an electric field to drive motion.
- **Key Actuation Methods:**
  - **Electrostatic Actuation**:
    1. Common and widely used due to fast response and low power consumption.
    2. Actuators are typically based on capacitors that create force when voltage is applied between plates.
  - **Electrothermal Actuation**:
    1. Works by heating a material (via a microheater) to create movement.
    2. These actuators can produce a large driving force and displacement with low driving voltage.
  - **Electromagnetic Actuation**:
    1. Uses the Lorentz force (interaction of magnetic fields and current) to generate movement.
    2. Known for quick response and large displacement but typically requires a larger physical size.
  - **Piezoelectric Actuation**:
    1. Uses the piezoelectric effect, where certain materials change shape when an electric field is applied.
    2. These actuators are highly sensitive but have a small driving force and displacement per unit voltage.
- **Actuation in MEMS Devices**:
  - MEMS devices, such as those designed using **PolyMUMPs** or **MetalMUMPs**, often use embedded microheaters for electrothermal actuation.
  - The devices are typically actuated by applying sinusoidal forces (vibrations), and motion is described using an equation of motion involving mass (M), damping coefficient (b), spring constant (k), and force (F).
- **Key Considerations for Actuation**:
  - **Electrostatic Actuators**: Best for applications requiring fast response and low power consumption.
  - **Electrothermal Actuators**: Preferred for large displacement under low voltage.
  - **Electromagnetic Actuators**: Useful for quick responses and large displacement, but larger in size.
  - **Piezoelectric Actuators**: Known for their high sensitivity but limited driving force per unit voltage.

Electrostatic Actuation in MEMS Devices:

- **Electrostatic Actuation** relies on the electric field between two parallel plates with opposite charges. This works based on Coulomb's law, which explains the force between charges separated by a certain distance.
- **Advantages** of electrostatic actuation:
  - Simple design
  - Fast response time

    - Low power consumption
    - Easy to fabricate
- **Challenges** include:
    - Non-linearity
    - High driving voltage required
- **Types of Electrostatic Actuation**:
    - **Parallel Plate Actuation**:
        - Two plates (one movable, one fixed) with opposite charges.
        - The displacement depends on the voltage difference between the plates. If the charges are opposite, the plates attract each other, creating displacement.
        - **Problem**: Pull-in instability, which happens when the static friction causes the device to collapse.
    - **Comb-Drive Actuators**:
        - Involves interdigitated fingers that move closer or farther apart depending on the applied voltage.
        - Comb drives are used in many MEMS devices because they produce larger displacement and the force is less dependent on displacement.
        - **Advantages over parallel plate**: Larger displacement and force not as related to displacement.
- **Applications** of Electrostatic Actuation:
    - MEMS actuators, biosensors, humidity sensing, mass sensing, MEMS nanopositioning systems, RF MEMS switches, gyroscopes, and biomarker detection (e.g., acetone in breath for diabetes detection).
    - Used in industries like automobile GPS systems, MEMS oscillators, and gas sensors.
- **Driving MEMS Devices**:
    - To make MEMS devices vibrate, an AC voltage is applied between the plates of the stator and rotor.
    - Different driving modes:
        - **Simple Alternating Voltage** ($V1\sin\omega t$)
        - **Alternating Voltage with a DC Bias** ($V0 + V1\sin\omega t$)
        - **Push-Pull Driving** (Preferred for comb drive actuators)
    - **Push-Pull Driving** is often the best because it applies force to both sides of the rotor.

Electrothermal Actuation

- **Electrothermal Actuation** is mainly used in MEMS devices for generating movement with a desired displacement, though it is rarely used in sensing applications.
- **How it works**: An AC current is applied to a microheater made from different layers of materials. This causes a temperature difference across the materials, leading to thermal stress and bending of the device due to the mismatch in the coefficient of thermal expansion (CTE) between materials.
- The **cooling** happens through conduction (to the substrate) and convection (to surrounding air or liquid).
- **Changes in temperature** affect the device in two ways:
    1. It causes dimensional changes and stresses in the device.
    2. The material properties change with temperature.
- **Types of Electrothermal Actuators**:
    1. **U-Beam Actuator** (Hot/cold arm): Involves a narrow hot arm and a wide cold arm. The hot arm expands more due to higher resistance, generating thermal stress.
    2. **Bimorph Actuator**: Composed of two materials with different thermal expansion, causing the device to bend when current is applied.
    3. **Thermal Buckling Actuators**: Uses a V-beam or shuttle beam, where heating causes the beam to expand and move.

- **Advantages**:
    1. Large displacement.
    2. Easy to fabricate.
    3. Requires low excitation voltage.
    4. High force with relatively low applied voltage.
- **Disadvantages**:
    1. Requires a large amount of current and low-voltage amplifier.
    2. Consumes high power due to Joule heating.
    3. Sensitivity to ambient temperature.
    4. Excess heat can affect nearby electronics and packaging.
- **Applications**:
    1. MEMS sensors, biosensors, humidity sensing, gyroscopes, and others.
    2. **Example**: A humidity sensor using titanium dioxide (TiO2) nanoparticles, with output measured by a piezoresistive sensor, showed a linear increase in sensitivity with temperature.

Electromagnetic Actuation

- **Electromagnetic actuation** uses **Lorentz force** (the combined electric and magnetic forces on a point charge) to generate a magnetic field in a resonator. This force is generated by applying alternating current (AC) to a coil or inductor integrated into the resonator.
- **Lorentz Force**: When a current flows through a conductor placed in an external magnetic field, it generates a force perpendicular to both the current and the magnetic field. This force causes a mechanical displacement, creating motion in MEMS devices.
- **Types of Actuators**:
    1. **In-plane actuator**: The current flows through a microbeam within a magnetic field, creating displacement in the plane (Fig. 7a).
    2. **Out-of-plane actuator**: Alternating current through the device generates motion in the perpendicular direction (Fig. 7b).
    3. **Micro-coil actuator**: A coil deposited on a microbeam creates opposite Lorentz forces at different points on the coil, causing net motion (Fig. 7c).
- **Advantages**:
    1. Large displacement without nonlinearity.
    2. Lower voltage requirements (current-driven, not voltage-driven).
    3. High reproducibility and rapid response.
    4. High accuracy and easy control.
    5. Ideal for MEMS devices due to high driving force for device size.
- **Disadvantages**:
    1. Requires large currents, leading to high power consumption.
    2. Complex fabrication, including the need for inductive parts and deposition of magnetic materials.
    3. Limited applications due to the challenges of using large currents and manufacturing complexities.
- **Applications**:
    1. **MEMS switches**.
    2. **Optical switches**.
    3. **Micro scanners**.
    4. **Gyroscopes**.
    5. **Relays**.
    6. **Humidity sensors** (e.g., using ZnO NRs and chitosan SAMs).

Piezoelectric Actuation

- **Piezoelectric Effect**: The ability of certain materials to produce an electrical voltage when subjected to mechanical stress. Discovered by the Curie brothers in 1880, with "Piezo" meaning "press" or "push" in Greek.
- **Piezoelectric Actuators**: These transducers convert an applied electrical potential into mechanical movement or strain based on piezoelectricity. Materials commonly used for piezoelectric actuators in MEMS (Microelectromechanical Systems) include quartz, zinc oxide, lead zirconate titanate (PZT), and polyvinylidene difluoride (PVDF).
- **Working Principle**:
  - A thin piezoelectric layer is placed between electrodes within the MEMS beam.
  - When a voltage is applied to the piezoelectric material, it expands according to the polarization of the voltage, causing axial bending of the beam.
- **Advantages of Piezoelectric Actuators**:
  - High output force
  - Good operating bandwidth
  - Compact size and lightweight
  - Low power consumption
  - Fast response time
- **Drawbacks**:
  - Small displacement range
  - High sensitivity to temperature
  - Nonlinear behavior and hysteresis (limits application range)
  - Brittle materials, often requiring additional flexible structures for actuation and sensing
- **Applications**:
  - Used widely in sensors and actuators, especially in MEMS.
  - **Example studies**:
    - **Humidity sensing** using piezoelectric microcantilevers.
    - **Dew point measurements** using Thin-film Piezoelectric-on-Silicon (TPoS) resonators with ZnO NRs.
    - **Chemical sensing** using piezoelectric excitation.
    - **Gas sensing** in defense applicans with piezoelectric MEMs

Actuation Techniques Discussion

- **Different MEMS Actuators**: MEMS actuators require specific drive electronics, depending on the actuation mechanism. The main types include:
  1. **Electrostatic Actuation**
  2. **Electrothermal Actuation**
  3. **Electromagnetic Actuation**
  4. **Piezoelectric Actuation**
- **Electrostatic Actuators**:
  1. **Advantages**: Simple design, fast response time, low power consumption, and ease of fabrication.
  2. **Disadvantages**: Non-linearity and high driving voltage requirements.
  3. **Applications**: Common for MEMS devices due to ease of use.
- **Electrothermal Actuators**:
  1. **Working Principle**: Require high current rather than high voltage for operation. They have low resistance to drive sources.
  2. **Disadvantages**: Not energy-efficient as they require high current. High voltage amplifiers are not ideal; low voltage and high current sources are needed.
  3. **Applications**: Used in MEMS where current-driven actuation is feasible.
- **Electromagnetic Actuators**:
  1. **Advantages**: Best for achieving maximum driving force per device size ratio.

    2. **Disadvantages**: High power consumption due to the large current used. Complicated fabrication process (requires inductive parts, coils, and magnetic material deposition).
    3. **Applications**: Effective for high force applications in MEMS.
- **Piezoelectric Actuators**:
    1. **Advantages**: Lower driving voltage requirements than other actuators, especially for resonance applications.
    2. **Disadvantages**: Still require high voltage amplifiers for certain uses.
    3. **Applications**: Used in applications requiring resonance, such as sensors.
- **Recent Trends**:
    1. There is growing interest in MEMS-based sensor devices, with many now being actuated using the above techniques.
    2. MEMS sensors offer high sensitivity and resolution, and are becoming more robust and reliable due to integrated configurations.
- **Applications**: MEMS actuators are being used across a range of fields, with rising development in micro-assembly and micromanipulation for sensor applications.

Sensing Mechanisms for MEMS-based Devices

- **Sensing Mechanisms**: The sensing mechanism is crucial for detecting the output signal from MEMS devices. It typically relies on changes in mass, stress, electrical, or mechanical characteristics of the device.
- **Common Sensing Techniques**:
    1. **Piezoresistive**: Measures the changes in electrical resistance due to stress or deformation of the material. It is highly temperature-dependent and easy to integrate with a Wheatstone bridge readout circuit.
    2. **Capacitive**: Measures changes in the frequency or amplitude of a signal using parallel plates. It is known for simplicity, high sensitivity, low drift, low power consumption, and can use MS3110 capacitive readout circuits.
    3. **Optical**: Based on molecular absorption spectroscopy, which emits photons when atoms are excited. It has good feasibility but is expensive and complex to implement.
- **Polymer-based Detection**: A polymer deposited on the MEMS device absorbs a particular chemical, leading to changes in stress or mass that can be measured. This can be detected by:
    1. **Resonant Frequency Measurement**: The change in mass causes a shift in the resonant frequency.
    2. **Piezoresistor**: A piezoresistor on the surface of the sensing element can be used to estimate the mass change.
    3. **Thermocouples**: Temperature changes caused by the heat generated when the polymer absorbs the analyte can also be used for detection.
- **Advantages and Disadvantages**:
    1. **Optical Sensing**: While feasible, it is expensive compared to capacitive and piezoresistive techniques.
    2. **Capacitive and Piezoresistive Sensing**: These are common and more affordable methods. CMOS-MEMS devices can incorporate both sensing techniques, while PolyMUMPs and MetalMUMPs devices are typically designed for capacitive sensing only.
- **Applications**: These sensing techniques are widely used in MEMS devices due to their efficiency in measuring changes in physical properties and enabling precise control and monitoring in various applications.

Piezoresistive Sensing

1. **Principle of Operation**:

- Piezoresistive materials change their electrical resistance when they are under strain or stress. This change in resistance can be used to measure mechanical stress.
- When stress is applied to the material, its resistance changes based on the surface-stress changes, especially when the material bends.

2. **Key Formula**:
   - The resistance (R) of a piezoresistor depends on its resistivity (ρ), length (l), and cross-sectional area (A):

     $$R = \frac{\rho l}{A}$$

   - The change in resistance (ΔR) is proportional to the applied strain (ε) and the gauge factor (G):

     $$\Delta R = G \times \varepsilon \times R$$

3. **Types of Strain**:
   - **Longitudinal Strain**: Affects the length of the material.
   - **Transverse Strain**: Affects the width or cross-sectional area of the material.
4. **Challenges**:
   - **Temperature Sensitivity**: Piezoresistive materials are sensitive to temperature changes, which can affect their resistance.
   - **Solution**: This is mitigated using a Wheatstone bridge, which minimizes the temperature effect by using multiple resistors in a configuration to balance out the temperature dependence.
5. **Wheatstone Bridge**:
   - A Wheatstone bridge circuit is used to measure small changes in resistance. It consists of four resistors arranged in a diamond shape.
   - Different configurations (quarter-bridge, half-bridge, and full-bridge) are used depending on how many active resistors change due to external factors like pressure, temperature, etc.
6. **Applications**:
   - Piezoresistive sensing is used in **bio/chemical detection**, **humidity sensing**, **switch applications**, **biomarker detection in exhaled breath**, **micro scanners**, **pressure sensing**, and **mass-sensitive gas sensors**.
7. **Materials**:
   - Common materials used are **silicon** and **polysilicon**. Silicon's resistivity changes based on the type of doping (N-type or P-type), affecting sensitivity.
8. **Challenges with Semiconductor Materials**:
   - **Longitudinal and transverse gauge factors** are small in semiconductor materials like silicon. The main change in resistance comes from changes in resistivity rather than geometry changes.
9. **Recent Developments**:
   - Researchers have developed **CMOS-based piezo-resonators** for **mass sensing applications**, showing high mass sensitivity and resolution, useful in applications like aerosol sensing.

Capacitive Sensing

1. **Overview of Capacitive Sensing Mechanism**:
   - Capacitive sensing measures changes in capacitance between two electrodes, typically either between stator and rotor fingers or between fixed and movable plates.
   - This method is favored in micromachined applications due to:
     - Compatibility with various fabrication methods.
     - High structural stiffness.
   - Notable features:

        - High sensitivity.
        - Low power consumption.
        - Simple design.
        - Minimal drift and low-temperature dependency.
2. **Application in MEMS Devices**:
    - **CMOS-MEMS and PolyMUMPs Devices**:
        - Utilizes a single parallel plate to detect variations in natural frequency or amplitude.
        - Capacitance in a non-actuated state Cs0Cs0Cs0 is based on:
            - The permittivity εεε, area AsAsAs, and gap z0z0z0.
        - When displaced, capacitance changes according to the new gap (calculated using relevant formulas).
    - **MetalMUMPs Devices**:
        - Incorporates differential comb fingers for capacitive output detection.
        - Static capacitance C0C0C0 for vibrating-fixed fingers is calculated using:
            - Overlapping finger area lf×wflf \times wflf×wf, gap ddd, and number of comb fingers nnn.
        - When moved by displacement yyy, capacitances C1C1C1 and C2C2C2 adjust based on movement, with changes calculated to reflect output voltage.
3. **Practical Applications**:
    - Capacitive sensing is integral to various MEMS devices:
        - MEMS resonators, biosensors, humidity sensors, diabetes screening tools.
        - Navigation (automobile GPS), low-noise accelerometers, and RF MEMS capacitive switches.
4. **Additional Details**:
    - MS3110 capacitive readout circuit translates capacitance changes into voltage changes in response to microheater temperature.
    - **Piezoresistance in Polysilicon**:
        - Table of longitudinal (πLπLπL) and transverse (πTπTπT) piezoresistance coefficients for P-type and N-type polysilicon:

- P-type: $\pi L = 58.8 \times 10^{-11}$/Pa, $\pi T = -18.5 \times 10^{-11}$/Pa
- N-type: $\pi L = -45.4 \times 10^{-11}$/Pa, $\pi T = 34.5 \times 10^{-11}$/Pa

Optical Detection - Simplified Notes

1. **Mechanism**: Optical sensing works by detecting differences between transmitted and received light.
2. **Detection of Compounds**: This method, called spectral transmission, is widely used for detecting specific compounds because it doesn't need chemical reactions or catalysts.
3. **Air Pollutants Detection**:
    - Optical sensors detect pollutants based on properties like absorption, refractive index, Raman scattering, fluorescence, and reflection.
    - Techniques include FTIR (Fourier Transform Infrared Spectroscopy), SPR (Surface Plasma Resonance), DOAS (Differential Optical Absorption Spectroscopy), LDAS (Laser Diode Absorption Spectroscopy), CRDS (Cavity Ring-Down Spectroscopy), NDIR (Non-Dispersive Infrared Spectroscopy), LIDAR, UV fluorescence, and chemiluminescence.
4. **Beer-Lambert Law**: This law explains how transmitted light (I) changes as it passes through a sample, with received light as I0I_0I0, absorptivity as α\alphaα, and path length as lll.
5. **Applications**:
    - While optical MEMS (Micro-Electro-Mechanical Systems) are mainly used in communications, they are also useful in air quality monitoring.

    - Optical sensors help identify chemicals and measure their concentration levels.
6. **Example Techniques**:
    - **Infrared Spectrometry**: Used for chemical detection through infrared light analysis.
    - **Optical MEMS Accelerometer**: Simulated results showed high sensitivity and low cross-sensitivity, useful for improving MEMS navigation devices.
    - **Fabry–Perot Optical Sensor**: Uses light to analyze gas in a chamber, detecting changes in light based on gas composition.
7. **Catechol Detection Using Optical MEMS**:
    - A specific example where blue light (472 nm) detects catechol oxidation.
    - Light is directed through a MEMS device, and data is collected via a spectrophotometer connected to a computer.

Sensing Mechanisms Discussion (Simplified Notes)

1. **Types of Sensing Mechanisms:**
    - **Piezoresistive:** Detects small changes in stress by measuring the change in resistance.
    - **Capacitive:** Measures changes in capacitance between components like plates or comb fingers.
    - **Optical:** Detects changes in transmitted light to sense changes in the environment.
2. **Advantages and Disadvantages:**
    - **Optical Sensing:**
        - *Advantages:* Highly feasible and sensitive.
        - *Disadvantages:* Expensive to implement compared to capacitive and piezoresistive methods.
    - **Piezoresistive Sensing:**
        - *Advantages:* Can detect very small changes in stress.
        - *Disadvantages:* Sensitive to temperature changes, which can affect its accuracy.
    - **Capacitive Sensing:**
        - *Advantages:* Common, cost-effective, and reliable.
        - *Disadvantages:* Can be affected by environmental factors.
3. **Applications and Advancements:**
    - Recent progress in **actuation** and **sensing** has led to improved sensors for gas and humidity sensing, as well as health monitoring.
    - MEMS sensors provide **high resolution**, **sensitivity**, **repeatability**, and **rapid response**.
    - These sensors can be **miniaturized** and integrated with **on-chip electronics** for use in applications like **Internet of Things (IoT)**, enabling real-time, remote sensing, such as moisture tracking.
4. **Table 3**: Lists recent work over the last 5 years, focusing on actuation mechanisms, sensing materials, fabrication technology, and applications of MEMS sensors.

Discussion (Simplified Notes)

1. **Energy Harvesting and Power Sources:**
    - New technologies are emerging to harvest energy from the environment, specifically for micro and nano systems.
    - **Triboelectric Nanogenerators (TENGs)** convert mechanical energy into electrical energy through friction between two materials with opposite charges.
    - These devices have potential applications as self-powered sensors, especially for **biomechanical energy** generated from human activity.
2. **Low Power and Self-Powered Sensors:**
    - **Zero-power sensors** are being developed to reduce power consumption, enabling long-term operation or self-powering without external energy sources.

3. **Flexible Sensors:**
    - Flexible sensors have become popular for **health and human applications**. These sensors are versatile, used in wearable devices, and can serve as human-machine interfaces.
    - **Wearable electronics** are integrated with the human body for various functions such as **health monitoring** (heart rate, fitness tracking, etc.).
    - These devices are expanding in use for **hospital care**, **fitness and wellness tracking**, **human-machine interaction**, and **cognitive state recognition**.
4. **Future Trends with AI Integration:**
    - Combining **MEMS sensors** with **artificial intelligence (AI)** is expected to enhance the functionality of future sensors.
    - AI will help improve **human-machine interaction**, expanding applications in **sports training simulation**, **entertainment**, and **medical rehabilitation**.
    - The integration of **machine learning** in next-generation sensors will lead to **smart sensing systems**, offering more advanced and comprehensive user experiences.

Conclusions and Future Trends (Simplified Notes)

1. **Importance of MEMS Sensors:**
    - MEMS-based sensors are crucial in miniaturization and electronic microcircuits.
    - Understanding the actuation and sensing mechanisms is essential for MEMS devices' operation and output signal detection.
    - The article reviews recent trends in MEMS-based sensors and their actuation and sensing mechanisms.
2. **Advancement of MEMS Technology:**
    - This technology is evolving, with a focus on improving actuation and sensing techniques.
    - Proper understanding and selection of these mechanisms based on specific application needs (e.g., sensitivity, frequency, temperature) are vital for effective use.
3. **Emerging Trends:**
    - MEMS devices are moving towards more complex and versatile tasks beyond simple functions.
    - MEMS devices will continue to miniaturize, becoming more affordable while increasing in functionality and performance.
    - The demand for MEMS products is growing, and future fabrication techniques will evolve to meet these needs, reducing production cycles and increasing speed.
4. **Challenges Ahead:**
    - **Reliability**: Ensuring reliability and improving MEMS devices will be central to future research.
    - **New Materials and Cost-Effectiveness**: New materials and efficient fabrication methods are key to future advancements.
    - **Challenges in Current MEMS Technologies**:
        - **Sensitivity**: Traditional MEMS sensors using MOS thin films show poor sensitivity, limiting their effectiveness in certain applications.
        - **Nanomaterial Integration**: Integrating high-performance MOS nanomaterials with microheaters remains difficult due to control issues and low yield.
        - **Adhesion Issues**: Improving adhesion between microheaters and sensing materials, especially at high temperatures, is a challenge that affects stability and performance.
        - **Sensing Films**: Fabricating high-sensitivity sensing films using MEMS-compatible methods remains an urgent goal.
5. **Future Challenges:**

- **Power Supply and Flexibility**: Addressing challenges in power supply and flexibility, especially for wearable sensors and human-machine interface applications.
- **Data Analysis**: Overcoming issues related to the analysis of large data generated by MEMS sensors is a key focus for future development.